Coastal and Estuarine Studies 58

Coastal Hypoxia
Consequences for Living Resources and Ecosystems

Effects of Hypoxia on the Shrimp Fishery of Louisiana and Texas

Roger J. Zimmerman and James M. Nance

15

Effects of Hypoxia on the Shrimp Fishery of Louisiana and Texas

Roger J. Zimmerman and James M. Nance

Abstract

Large-scale hypoxia, recently approaching 20,000 km^2, overlaps with habitat and fishing grounds of commercial shrimp species in Louisiana and Texas shelf waters. It is expected that an environmental impact of this magnitude would have an effect on the shrimp population that is reflected in catch statistics. In this paper, we examine the geographic distribution and amount of shrimp catch in relation to location and size of the hypoxic zone. The results are interpreted in context with what is known about the life cycles and habits of the two shrimp species involved and the behavior of shrimp fisheries. A significant negative relationship was evident between catch of brown shrimp from Texas and Louisiana waters versus the relative size of the mid-summer hypoxic zone. In addition, Texas catch was significantly dependent upon Louisiana catch, a relationship that has become stronger since 1980. Catch per unit effort of brown shrimp also has declined significantly during a recent interval in which hypoxia was known to expand. Importantly, the same relationships were not significant between hypoxia and catches of white shrimp. As hypothesized, owing to their more offshore habitat requirements, brown shrimp were impacted to a greater degree than white shrimp. The annual success of shrimp fisheries, like most commercial fisheries, is highly related to environmental factors. The combined evidence indicates that hypoxia in Louisiana, due to its large area of coverage, has increased as an environmental factor for shrimp in recent decades.

Coastal Hypoxia: Consequences for Living Resources and Ecosystems
Coastal and Estuarine Studies, Pages 293-310

Published in 2000 by the American Geophysical Union

Introduction

Historical Background

Louisiana and Texas shrimp fisheries depend primarily upon two species of shrimp, the brown shrimp [*Farfantepenaeus* (formerly *Penaeus*) *aztecus*] and the white shrimp [*Litopenaeus* (formerly *Penaeus*) *setiferus*], as revised [Perez-Farfante and Kensley, 1997]. The life cycles of these species are geographically wide ranging, encompassing inshore estuarine habitats as well as offshore shelf waters. The primary white shrimp fishing grounds are inshore (coastal bays) and nearshore (from the beach out to 10 fm (18 m)), extending from the Mississippi River to the upper Texas coast. The main U.S. brown shrimp fishing grounds are nearshore and offshore (deeper than 10 fm (18 m)), extending from the Mississippi River to the Texas/Mexico border. In Louisiana, the offshore life stages of white shrimp and brown shrimp inhabit areas that overlap with the hypoxic zone [Downing et al., 1999].

Commercial fishermen are characteristically opportunistic and are continually searching for new ways to increase their catch. When the shallow-water shrimp fishery of the first half of the 20th century evolved from using beach seines and sailing ships to motorized vessels, the harvest capability extended into deeper shelf waters. The discovery of abundant brown shrimp grounds in deep waters during the 1950s further stimulated expansion of the offshore fishery through use of large trawling vessels with multiple nets. When the nearshore catch of white shrimp declined in the late 1940s, brown shrimp became targeted both nearshore and offshore, and the overall harvest was maintained [Moffett, 1967].

Louisiana shrimp fishery. Louisiana's early shrimp fishing industry, prior to the 1950s, was based upon catches of white shrimp. With its inshore and nearshore life cycle, this species was a favorite of commercial fishermen from the time of early settlements in the region. When white shrimp declined during the late 1940s, the Louisiana shrimp fishery shifted and catches became increasingly dominated by juvenile brown shrimp [Condrey and Fuller, 1992].

Louisiana has a complex system of open and closed fishing seasons that focus on shrimp in inshore and nearshore territorial waters (within 3 nmi (5.5 km) of shore). The Louisiana Wildlife and Fisheries Commission sets the dates of closures annually within each of three coastal zones. Accordingly, Louisiana inshore waters are closed from December until late May, open from late May into July, closed again from a date in July until late August, and re-opened from late August into December [Louisiana Department of Wildlife and Fisheries, 1992]. The annual harvest of juvenile brown shrimp in Louisiana begins during the latter part of May. This allows an unlimited number of fishing craft access to the small brown shrimp as they exit estuarine systems. Importantly, federal waters of the Exclusive Economic Zone (EEZ) offshore of Louisiana are open throughout the year.

Texas shrimp fishery. The Texas shrimp fishing industry was developed primarily during the 1950s with the discovery of adult brown shrimp grounds in offshore waters. The industry is dominated by large trawlers that pull as many as four nets apiece (quad-rigged) and target high valued large shrimp. The substantial growth of the U.S. shrimp fishery after 1960 is based upon brown shrimp [Christmas and Etzold, 1977].

Texas, like Louisiana, opens its inshore bays to commercial shrimp fishing in May, but closes nearshore and offshore waters from mid-May until mid-July. In Texas, the number of fishing craft are limited inshore, thus allowing escapement of juvenile brown shrimp into offshore waters where they continue to grow. When the Texas closure ends in mid-July, an unlimited number of fishing vessels have access to the offshore shrimp population of larger size individuals. The closure in Texas has been in existence in territorial waters (within 9 nmi (16.5 km) of shore) since 1959, and was extended to federal waters (from 9 to 200 nmi (16.5 to 1000 km)) beginning in 1981 [Klima et al., 1982].

Value and characteristics of the fishery. The Louisiana and Texas shrimp fishery is consistently one of the most valuable in the U.S. During 1998, Louisiana and Texas together landed 168.6 million pounds of shrimp tails (60.7% of the nation's total) with a dockside value of $312.9 million [Holiday and O'Bannon, 1999].

Shrimp are an annually renewable resource that is considered fully exploited [Nance and Harper, 1999]. Shrimp fishermen are highly flexible and are ready to expand or reduce fishing effort each year depending upon the magnitude of the shrimp crop. Due to this practice, annual shrimp fishing effort and shrimp landings are closely correlated and are reflective of the annual abundance of shrimp. Shrimp landings/abundance vary widely from year to year, and this variation is generally attributed to environmental factors.

Shrimp Life Cycle

Generalized reproductive cycle. The life cycle of commercial shrimp involves offshore (Gulf shelf) and inshore (estuarine) phases. Adults spawn on the Louisiana and Texas shelf. Planktonic larvae immigrate via currents into coastal estuaries. Within the estuaries, postlarvae metamorphose into small juvenile shrimp that are benthic in habit. After about two months, intermediate size juveniles emigrate from the nursery and return to the offshore shelf to complete their growth into adults. The life cycle from egg to adult takes about six months. Larval, postlarval, subadult and adult shrimp utilize habitats overlapping with the hypoxic zone, and, depending on which stage within the life cycle, their spawning grounds, feeding grounds or migratory pathways may be impacted.

Brown shrimp. Spawning by adult brown shrimp takes place in relatively distant shelf waters, from 8 to 60 fm (15 to 110 m) [Cook and Lindner, 1970; Christmas and Etzold, 1977]. Spawning occurs throughout the year and planktonic larvae move from offshore to inshore estuaries via currents. Peaks in the immigration of postlarvae occur during early spring and early fall. Juveniles use the tidal wetlands as nurseries to enhance growth and survival from March through November. After approximately two months inhabiting estuarine nurseries, the juveniles return as subadults to offshore Gulf waters. Large adults are abundant on the middle shelf where they spawn and renew the reproductive cycle. During migration on the shelf, brown shrimp have been observed to move as far as 335 nmi (620 km) [Sheridan et al., 1987].

White shrimp. Spawning by adult white shrimp occurs mostly near the coast between 4.5 and 17 fm (8 and 31 m) [Lindner and Anderson, 1956; Lindner and Cook, 1970]. Due to their affinity for nearshore habitats, adult white shrimp are commonly found in proximity to larvae, postlarvae and juveniles. Unlike brown shrimp, white shrimp spawning is restricted mostly between April and August [Bryan and Cody, 1975]. Immigration of postlarvae from the Gulf to the estuaries begins in May, and two or more peaks occur from June through September [Baxter and Renfro, 1967]. Juveniles are abundant in estuarine nurseries from May through November. White shrimp have been observed to move as far as 150 nautical miles (278 km) during migration on the shelf [Lyon and Boudreaux, 1983].

Prior Evidence Suggesting Effects of Hypoxia

Past investigations suggest that shrimp and fish species may avoid hypoxic waters. Fishery-independent surveys, using bottom-trawls, reveal reduction or complete absence of shrimp and fishes in waters with very low oxygen content. Both the abundance and biomass of finfishes and shrimps are significantly less where oxygen concentrations in bottom water fall below 2 mg l^{-1} [Leming and Stuntz, 1984; Renaud, 1986a]. Several scenarios are possible – the shrimp or fish may die, they may move away either horizontally along the bottom or vertically upward in the water column, or they simply may not be attracted to the area for reasons other than hypoxia.

For shrimp, laboratory experiments substantiate that commercially dominant species have the ability to detect and avoid water with low oxygen concentration [Renaud, 1986b]. Under experimental laboratory conditions, white shrimp avoided water with dissolved oxygen lower than 1.5 mg l^{-1} and brown shrimp were even more sensitive and avoided water of less than 2.0 mg l^{-1} dissolved oxygen. It has been suggested that this ability to detect and avoid water with low oxygen leads to a blocking effect on shrimp emigrating from inshore nurseries to offshore feeding and spawning grounds. In a mark-recapture study of shrimp migration, juvenile brown shrimp leaving marsh nurseries were sometimes blocked from normal movement offshore by an environmental barrier [Gazey et al., 1982]. Also, offshore migration by brown shrimp was reported to be greater and catches larger during periods when hypoxia was not evident as compared to periods when hypoxia was observed [Renaud, 1986a]. Avoidance, or crowding, of shrimp and fish away from hypoxic waters has been repeatedly observed in phenomena called "jubilees" [Loesch, 1960].

Recent analyses further suggest a localized negative relationship between shrimp catch and hypoxia [Zimmerman et al., 1997]. Where hypoxia is widespread and persistent on the Louisiana shelf, the shrimp catch is always low. If blocking by hypoxia of shrimp migration offshore does occur, shrimp distributions and densities may be modified. Indeed, in Louisiana, the nearshore concentration of shrimp is orders of magnitude higher than in the hypoxic zone. Also, it is hypothesized that due to hypoxia shrimp movement is diverted laterally and parallel to the coast along with the current. The predominant movement appears to be westward. Such large-scale disruptions to shrimp distributions could be expected, because as much as 50% of the Louisiana shelf is affected by hypoxia during the summer months. This is the period when juvenile brown shrimp are migrating offshore and when adult white shrimp are spawning on the inner shelf.

In some instances, shrimp could move up in the water column as a short-term means of escaping bottom hypoxia. Such a move might substantially increase their exposure to predation and increase mortality. Also, it is not known to what degree shrimp are killed directly by oxygen levels too low to sustain life.

Shrimp Fishery Statistical Methods

Statistical Subareas

Shrimp statistics for commercial fisheries are collected by port agents located in coastal ports around the Gulf of Mexico. Currently, there are about 20 port agents employed by state or federal agencies participating in the Gulf Shrimp Statistics Program.

To facilitate the geographic assignment of commercial shrimp catch and catch per unit effort (CPUE), the continental shelf of the Gulf of Mexico has been divided into 21 statistical subareas (Fig. 1). Each of these subareas has been further divided between "inshore" (bays and sounds) and "offshore" (seaward from the shoreline). The inshore area is labeled depth zone zero. The offshore area comprises depth zones in 5-fm (9-m) increments extending to 45 fm (82 m) (identified as depth zone 1, depth zone 2, ... depth zone 9). The first two offshore depth zones are termed "nearshore", encompassing 0 to 10 fm (18 m). All shrimp fishery data collected in depths greater than 45 fm are included in the 45-fm depth zone for analysis. Thus, each of the 21 statistical subareas in the Gulf of Mexico has ten depth zones (one inshore and nine offshore). Each subarea/depth zone combination is a unique location within the Gulf of Mexico, and is termed a "location cell."

Determination of Catch and Effort

Port agents collect shrimp statistics from seafood dealers and fishermen. Data are obtained from dealer records on the species, size, amount and value of the shrimp that are unloaded or landed at the dealer's place of business. These data are referred to as "dealer data" in the landings file. Currently there are about 460 active seafood dealers in the Gulf of Mexico. A monthly canvas of dealers by port agents provides estimates of total weight in pounds of shrimp landed. The second type of data includes detailed information on fishing effort (CPUE) and location for each fishing trip and is collected by interviewing either the captain or a member of the crew. These data are referred to as "interview data" in the landings file.

Because the fishing trip is the basic sampling unit, the ideal situation is to collect both the landings and interview data on a trip-by-trip basis. The total weight caught in the fishery by trip would be considered a census; however, because of the large number of fishing trips that occur in the Gulf shrimp fishery (i.e., currently over 300,000 total trips), it is impossible for the interview record to include every fishing trip. Consequently, data collection procedures include two modifications that allow sampling of the total population. The modifications attempt to facilitate non-bias selection of vessels that have fished in the offshore areas [Nance, 1992, 1993].

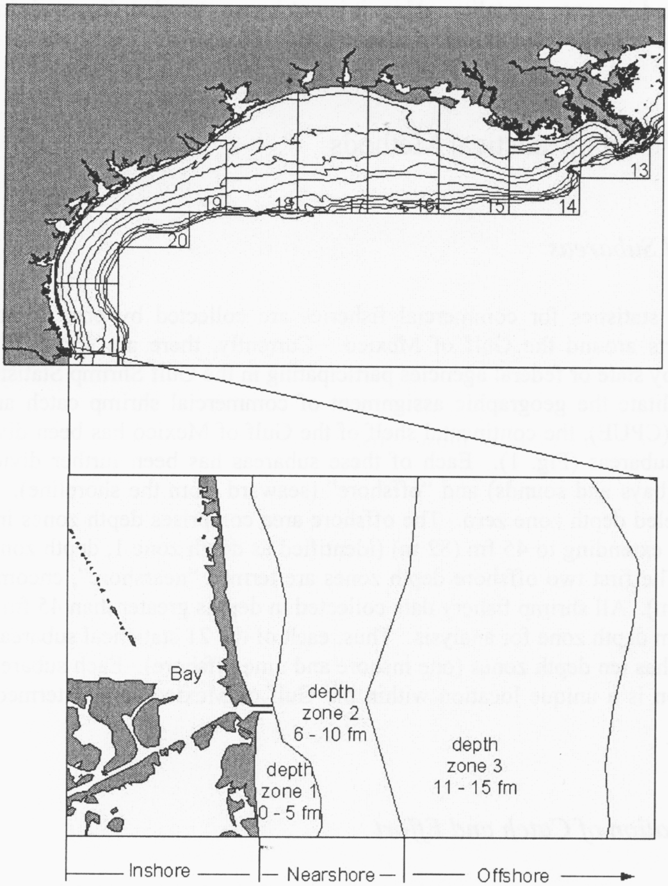

Figure 1. Subareas and depth zones used for collecting fishery data from Texas and Louisiana marine waters. The boundary between Louisiana and Texas is approximately the nearshore border of areas 17 and 18. (U. S. Dept. Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries, Service)

Estimation of shrimp fishery effort is dependent upon data summarized by location cell. To estimate fishing effort for each location cell on a monthly basis, there must be two elements of data for each cell: 1) the total weight of shrimp caught by species, and 2) the average catch per unit of effort (CPUE; pounds per 24-h fished). As mentioned above, the total pounds caught by species is acquired from commercial seafood dealers located along the Gulf coast, while CPUE is obtained from sample interviews with captains of shrimp vessels at the termination of their trip. Although the interview level has no effect on the collection of total pounds data, it does affect the estimation of average CPUE. Obviously, the more interviews that port agents can gather during a particular month, the more precise the estimate of average CPUE for that month. During peak shrimp production months, about 70-80% of the pounds of shrimp caught have an interview obtained average CPUE associated with them.

Monthly effort (days fished) for each location cell is estimated by dividing the

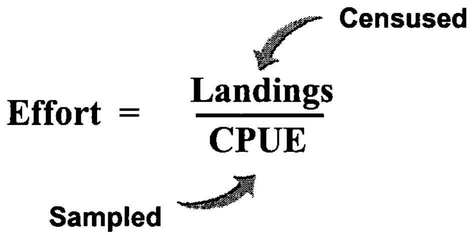

Figure 2. The relationship between shrimp catch, fishing effort and catch per unit effort (CPUE).

monthly shrimp landings from a location cell by the average CPUE obtained from interviews at the same time and location (Fig. 2).

For a few location cells, shrimp landings are reported, but there are no interviews from which to estimate CPUE. To account for the missing data, a statistical model was devised to estimate CPUE for those cells. Both the yearly variation in number of shrimp available and regional differences in shrimp abundance within the Gulf of Mexico play important roles in determining the CPUE for a given location cell. Therefore, a general linear model was developed to predict current CPUE with year and geographic location as the independent variables. Monthly differences in shrimp abundance were accounted for by using a different model for each month. Each of the 12 linear models is in the general form of:

$$\log \mathrm{CPUE}(ij) = \mu(ij) + \mathrm{year}(i) + \mathrm{location}(j) + \varepsilon(ij), \text{ where}$$

CPUE(ij) is the observed CPUE in year i at location cell j;
$\mu(ij)$ is the overall mean;
year(i) is the effect on CPUE due to year i;
location(j) is the effect on CPUE due to location j; and
$\varepsilon(ij)$ is a random error term with expected value 0 and equal variance for all i and j.

Total effort for any month is estimated by summing the effort estimates for each of the individual location cells. Total annual effort is calculated for descriptive purposes as the sum of the monthly efforts. Total effort is also used to estimate monthly and annual CPUE values.

Catch and Effort in Texas and Louisiana

Annual Trends and Distribution of Catch

The annual catches of brown shrimp and white shrimp have generally increased since 1960 (Fig. 3). Brown shrimp catch steadily increased, peaked at 103.4 million pounds (47 thousand metric tons) in 1990 and declined thereafter through 1998. White shrimp

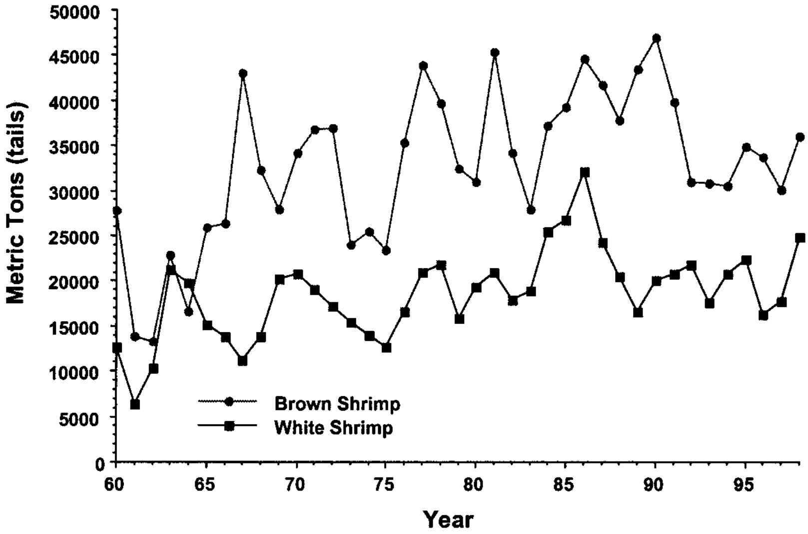

Figure 3. Trends in annual catch of brown shrimp and white shrimp in the western Gulf of Mexico, 1960-1998 (total weight of shrimp tails caught in Texas and Louisiana waters).

catch increased to a lesser degree than brown shrimp and peaked at 70.7 million pounds (32 thousand metric tons) in 1986.

The distribution of catches of white shrimp and brown shrimp from 1992 to 1998, a period of expanded hypoxia, are insightfully different. During the interval, most white shrimp were caught inside 10 fm (18 m) along the Louisiana and upper Texas coast (Fig. 4a). In both states, white shrimp juveniles were predominantly caught in bays and estuaries and the adults were caught nearshore along the coast as has been the case historically. Distribution of brown shrimp catch during this period was quite different from white shrimp and also differed between the two states (Fig. 4b). Louisiana brown shrimp catch was almost entirely of juveniles taken from bays, estuaries and shallow nearshore waters. In Texas, the brown shrimp catch was mainly comprised of subadults and adults taken in offshore waters. Most importantly, the catch of brown shrimp offshore of Louisiana was negligible, coincident with the area of the hypoxic zone (Fig. 4b).

Nearshore versus Offshore Catch in Texas and Louisiana

In Louisiana, the nearshore catch and effort within 10 fm (18 m) is always higher than beyond 10 fm. The large difference between nearshore and offshore catch in Louisiana is remarkable in comparison to nearby Texas (Fig. 5). Since shrimp in Louisiana are caught as they exit the inshore nurseries, they are small in size and, at least in theory, their productivity through growth to a larger size is unrealized. Production models conservatively estimate that several million of pounds are lost each year because of curtailed growth due to early harvest of shrimp [Nance et al., 1994]. In Texas, juvenile brown shrimp are allowed to grow to a larger size as they migrate offshore during a six-week closed season, which normally occurs between May 15 and July 15 of each year.

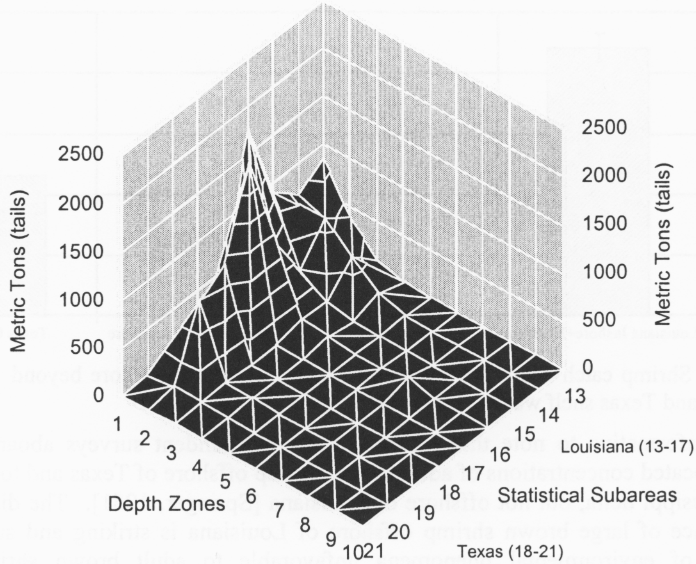

Figure 4a. Mean annual catch of white shrimp by subarea/depth location cell in the western Gulf of Mexico, during the 1992-1998 interval of expanded hypoxia on the Louisiana shelf. Subarea designations extend from the mouth of the Mississippi (Subarea 13) to the mouth of the Rio Grande (Subarea 21). Depth zones are in 5-fm (9-m) increments.

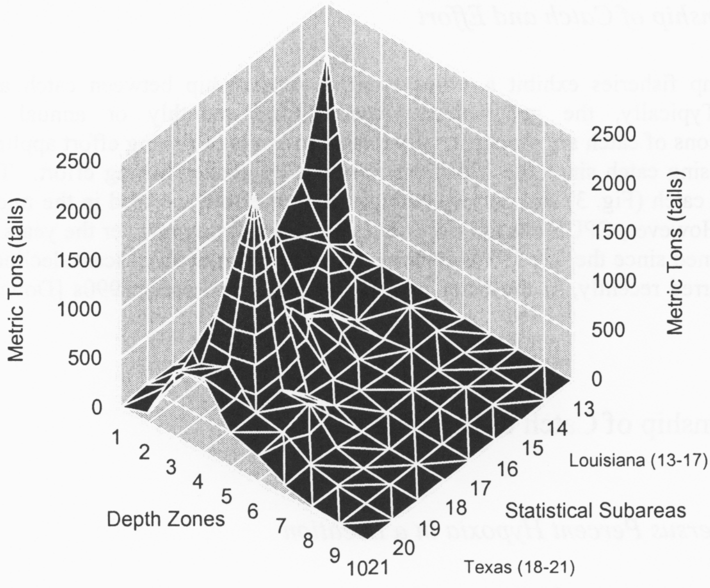

Figure 4b. Mean annual catch of brown shrimp by subarea/depth location cell in the western Gulf of Mexico, during the 1992-1998 interval of expanded hypoxia on the Louisiana shelf. Subarea designations extend from the mouth of the Mississippi (subarea 13) to the mouth of the Rio Grande (subarea 21). Depth zones are in 5-fm (9-m) increments.

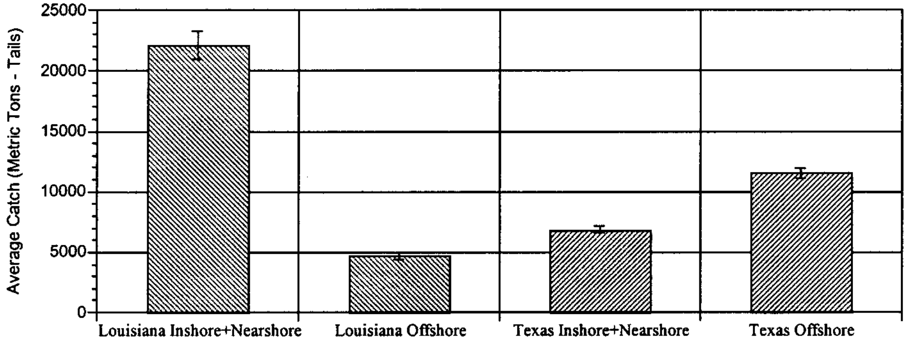

Figure 5. Shrimp catch nearshore within 10 fm (18 m) versus offshore beyond 10 fm from Louisiana and Texas shelf waters, 1960-1998.

It is informative to note that earliest fishery-independent surveys aboard the R/V *Oregon* located concentrations of adult brown shrimp offshore of Texas and to the east of the Mississippi delta, but not offshore of Louisiana [Springer, 1951]. The discontinuity and absence of large brown shrimp offshore of Louisiana is striking and suggests the presence of environmental phenomena unfavorable to adult brown shrimp. The observation also suggests that unfavorable conditions (hypoxia or something else) pre-date recent times.

Relationship of Catch and Effort

Shrimp fisheries exhibit a strong positive relationship between catch and fishing effort. Typically, the geographical (spatial) and monthly or annual (temporal) distributions of catch are proportionally related to hours of fishing effort applied. Trends in increasing catch since the 1960s are mirrored by greater fishing effort. The highest levels of catch (Fig. 3) and correspondingly highest effort occurred in the middle to late 1980s. However, CPUE has not necessarily remained the same over the years but in fact has declined since the late 1970s [Nance, 1989]. The most significant decline in CPUE has occurred recently, in the latter part of the 1980s and early 1990s [Downing et al., 1999].

Relationship of Catch to Hypoxia

Catch versus Percent Hypoxia in a Location

A negative relationship between the magnitude of catch and the degree of hypoxia at locations on the Louisiana shelf has been demonstrated previously [Zimmerman et al., 1997]. Annual maps depicting location and configuration of the hypoxic zone [Rabalais et al., 1991, 1992, 1998, 1999, unpublished data] were transferred to a geographic information system (GIS) format. These hypoxia maps, derived from single mid-summer cruises and despite potential error in representation, are the best spatial data available. The GIS hypoxia data were layered with annual shrimp catch data from location cells identified as geographically defined subareas and depth zones (Fig. 1). The annual percent of hypoxic area within each location cell was calculated for each year from 1985 through 1994. The average of July and August shrimp catch (all species combined) from each location cell was determined for corresponding years. It was assumed that July and August were months in which shrimp catch was most immediately impacted by hypoxia. A step-wise regression was performed using catch in location cells as the dependent variable and depth, subarea, east-to-west location, years and percent area of hypoxia as independent variables. Similar regressions were performed using CPUE and catch per unit area as dependent variables.

These analyses revealed a strong negative relationship between shrimp catch and the amount of area covered by hypoxia within location cells [Zimmerman et al., 1997]. A negative relationship also existed between catch and depth. However, no relationship existed between CPUE and hypoxia or depth. As noted, all species of shrimp were combined in these analyses.

The results were interpreted as evidence supporting hypotheses (1) that localized shrimp catch is negatively related to the amount of local coverage by hypoxia, and (2) that shrimp migration to offshore habitat is blocked by hypoxia. Although declining catch in relation to depth is a confounding factor, in adjacent Texas waters the catch increases with depth (Fig. 5). Also, the absence of shrimp in deeper shelf waters in Louisiana, beyond the hypoxic zone, could be interpreted as evidence of blocked migration. The lack of a relationship between CPUE and hypoxia is easily explained since shrimp fishermen do not put down their large main nets unless shrimp are present (i.e., hypoxic areas are rarely if ever trawled). Small trawls called "try nets" are used first to sample the bottom for shrimp in advance of deployment of full-size commercial trawls.

Overall Catch versus Relative Area of Hypoxia

If hypoxia causes localized catch to diminish, then the cumulative effect of an expanding hypoxic zone should be reflected in a reduction of the overall catch. To test this hypothesis, we examined the relationship between the annual shrimp catch and the area of mid-summer hypoxia between 1985 and 1997. The hypoxic area estimates were provided by N. N. Rabalais (personal communication) and were used as a relative measure of differences in the scale of hypoxia among years. Data on catches of brown shrimp and white shrimp from Louisiana and Texas from the months of July and August combined, as well as the annual total, were used in separate analyses. Regressions of July and August catch by species versus area of hypoxia were performed. The present analyses differ from the previous study [Zimmerman et al., 1997] by using overall catch, rather than catch at specific locations, and total area of hypoxia, rather than local area of hypoxia.

The results disclosed a significantly negative relationship between catch of brown shrimp and the area of hypoxia ($P = 0.02$, $n = 13$) from combined catches of Texas and Louisiana during the months of July and August (Fig. 6). The catch from Louisiana alone during July and August was weakly related ($P= 0.1$, $n = 13$) to the mid-summer

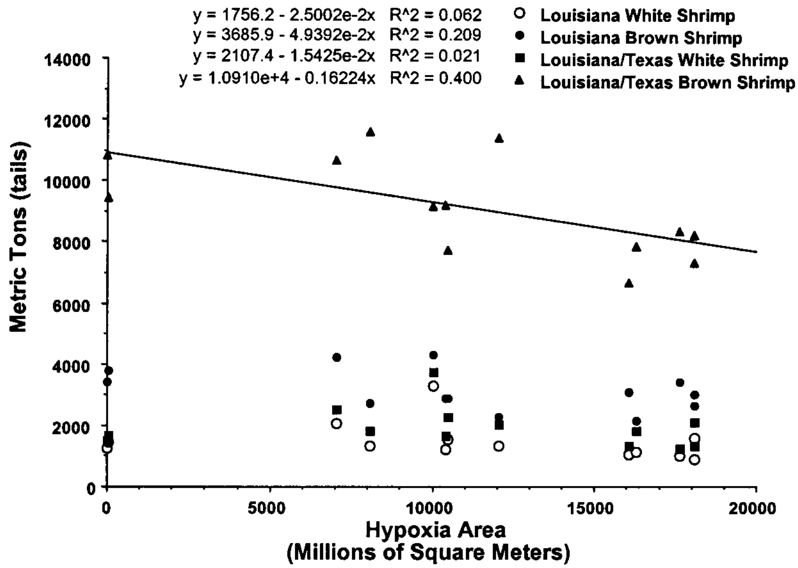

Figure 6. July and August brown shrimp catch from Texas and Louisiana versus relative size of the hypoxic zone on the Louisiana shelf during the years from 1985 through 1997.

area of hypoxia. Texas brown shrimp catch alone during July and August was not significantly related to area of hypoxia. White shrimp catch in either state and in both states combined, during July and August and for the annual total, was not significantly related to the area of hypoxia.

The negative relationship between area of hypoxia and catch of brown shrimp in Louisiana and Texas is relatively strong and remarkable. We suggest that the relationship involves negative environmental effects imposed upon the offshore habitat used by a brown shrimp population common to both states. In this case, the effect of annual size, timing and configuration of hypoxia in Louisiana becomes important to the catch of both states.

In a straightforward cause-and-effect circumstance, when hypoxia expands, the overall population of brown shrimp, as well as catch and CPUE in the fishery, would be reduced. A decadal trend in decline of CPUE in the brown shrimp fishery coincides with expansion of hypoxia. Since 1980, CPUE has decreased significantly even though effort declined through the 1990s. Changes in brown shrimp mean CPUE during each decade since 1960 demonstrate the downward trend of the 1980s and 1990s, i.e., 1960s = 12.9 kg h^{-1}, 1970s = 12.6 kg h^{-1}, 1980s = 11.2 kg h^{-1}, 1990s = 9.1 kg h^{-1} [Downing et al., 1999]. To further explore the possible relationship of expanded hypoxia and reduced CPUE, we examined the annual data of Texas and Louisiana combined. We found that since 1960, brown shrimp CPUE has declined significantly and the greatest decline has occurred after the mid-1980s (Fig. 7). By comparison, white shrimp CPUEs also declined, but not significantly since 1960. The difference in potential effects of hypoxia on CPUE of brown shrimp and white shrimp are consistent with differences in the nearshore versus offshore life cycles of the two species.

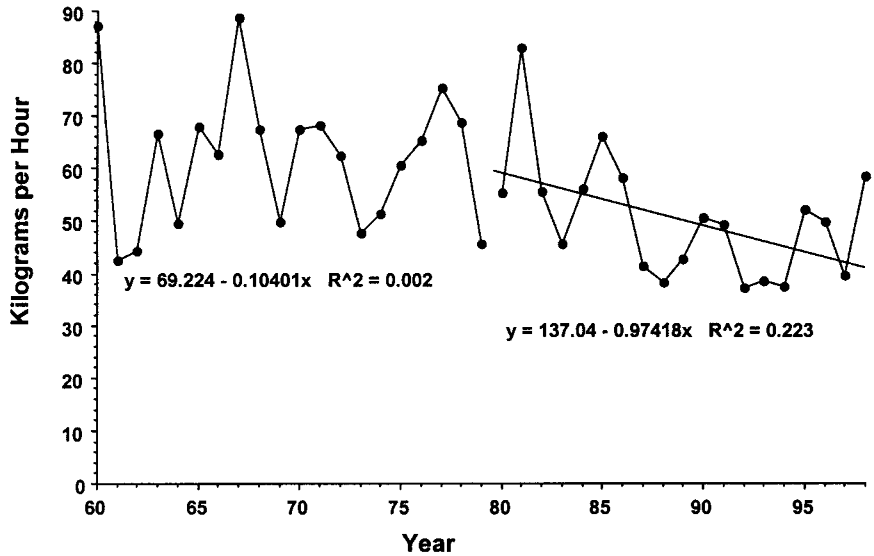

Figure 7. Trend in annual brown shrimp catch per unit effort (CPUE) from Texas and Louisiana from 1960 through 1998.

Jurisdictional Fisheries and Shrimp Populations

Louisiana versus Texas Shrimp Populations

The close correlation between the Texas brown shrimp catch and the Louisiana catch implies a surprisingly strong connection between the populations of each state. We propose that the magnitude of this relationship may, at least in part, result from the effects of hypoxia. Thus, if juvenile brown shrimp are blocked from migrating offshore by hypoxia, they may move laterally down-current into Texas waters. Brown shrimp that are not captured by the Louisiana nearshore fishermen contribute to the catch in Texas.

If blocking of brown shrimp migration into offshore Louisiana waters is a factor, the relationship between Louisiana and Texas could be stronger during years of expanded hypoxia. The larger the number of shrimp that cannot move offshore, the more to go elsewhere including escapement to Texas. Our regression of Texas catch, as the dependent variable, versus Louisiana catch revealed a significant positive relationship during the years from 1980 to 1998 (Fig. 8). During the earlier period, from 1960 to 1979, the relationship was not significant. We interpret this comparison as evidence supporting a greater blocking effect and expansion of hypoxia since 1980.

Unlike brown shrimp, regression analyses of white shrimp catch revealed no significant relationship between Texas and Louisiana. Two factors are likely involved that contribute to the difference between these two species. Firstly, white shrimp do not migrate as far as brown shrimp during their life cycle. Secondly, white shrimp do not

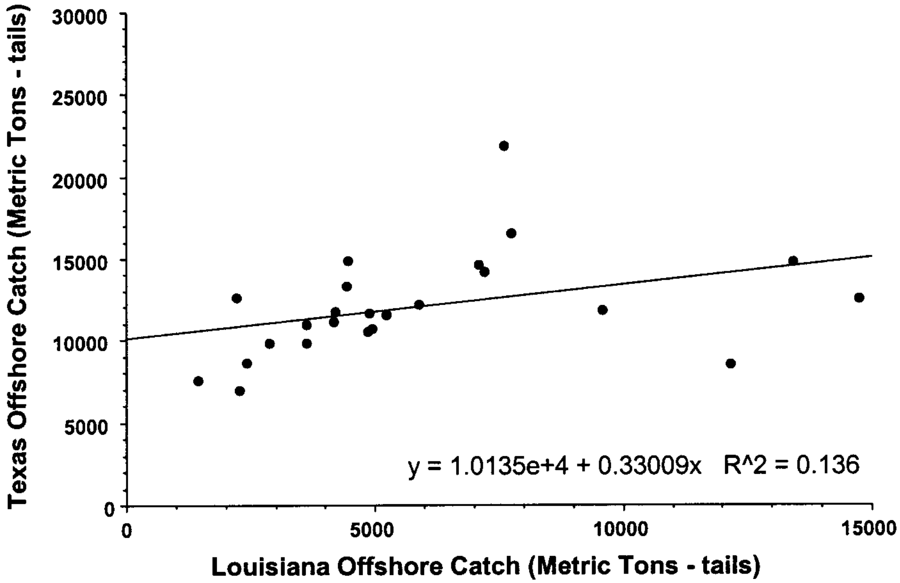

Figure 8a. Louisiana brown shrimp catch versus Texas brown shrimp catch from 1960 through 1979.

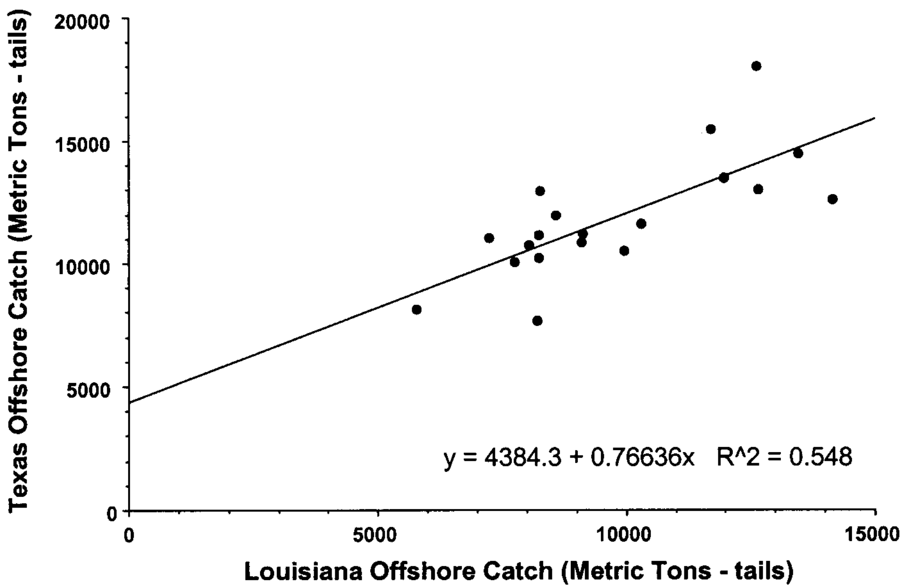

Figure 8b. Louisiana brown shrimp catch versus Texas brown shrimp catch from 1980 through 1998.

depend upon offshore habitats to the same degree as brown shrimp and thus are not as affected by the hypoxic zone.

Consequences of Hypoxic Zone Expansion

Reduction in Shrimp Catch

Recent evidence indicates that the catch in brown shrimp fisheries of Texas and Louisiana may decrease significantly when the hypoxic zone expands. During the years between 1985 and 1998, the area of hypoxia on the Louisiana shelf nearly doubled to 18,000 km^2 [Rabalais et al., 1998; Downing et al., 1999]. Within the interval, the brown shrimp catch declined from moderately high levels in the late 1980s (approximately 42 thousand metric tons per year) to low levels in the 1990s (approximately 32.5 thousand metric tons per year), coincident with hypoxia expansion. This reduction amounts to 22.6% of the previous catch, representing approximately 9.5 thousand metric tons less brown shrimp per year for Texas and Louisiana fisheries. The recent decline in CPUE in the brown shrimp fishery also corresponds with expansion in hypoxia. Average catch rates of brown shrimp changed from 11.2 kg h^{-1} to 9.1 kg h^{-1} from the 1980s to the 1990s [Downing et al., 1999]. Notably, white shrimp did not demonstrate the same recent declining trends in catch and CPUE as brown shrimp, but remained within the expected range of annual variability.

These changes in catch indicate an environmental impact to brown shrimp that did not affect white shrimp. The cumulative evidence suggests that the impact was caused by, or at least associated with, expansion of hypoxia. The negative effect of hypoxia on brown shrimp may co-vary with the negative effect of other factors, such as excessive freshwater in nursery areas or altered nursery habitat. Regardless of co-varying relationships, negative effects on catch appear to have been strengthened by greatly expanded hypoxia since 1990. Also, the details of how hypoxia affects brown shrimp in offshore waters are still unknown. It is not known whether cumulative environmental factors are involved nor whether negative effects on shrimp catch during one year translate to subsequent years.

Influence on Distribution of Catch and Effort

Spatial effect. During the late spring and throughout the summer months, when hypoxia occurs, the Louisiana nearshore and inshore shrimp fisheries are at their peak. These fisheries target juvenile shrimp as they emigrate from estuarine nurseries and when individuals are still relatively small in size and are not yet adults. If, as is hypothesized, expansive hypoxia blocks migration into deeper offshore waters, the effect would increase the concentration of shrimp occupying the nearshore shelf. Since shrimp fishermen target concentrations of shrimp, most of the trawling effort in Louisiana would remain nearshore. This appears to be the case, as exemplified by catch distributions (Figs. 4a and 4b). Thus, the relatively dense concentration of shrimp in the area between the hypoxic zone and the shoreline favors and perhaps helps to maintain the nearshore fishery in Louisiana.

Such is not the case in Texas where juvenile brown shrimp can migrate offshore without impediment. There, an offshore fishery is favored since the population can easily disperse across the shelf where individuals grow to adult size in deeper waters. Juveniles are fished by a restricted number of vessels within Texas bays, and subadult shrimp that emigrate out of the estuaries are protected by a temporary offshore fishery closure. Juveniles that escape the Louisiana fishery also can move down-current into Texas waters. This movement may cause a dependency of the Texas catch on Louisiana production. The apparent dependency has strengthened over the years, and since 1980 the success of brown shrimp in Texas has become significantly related to Louisiana catch (Fig. 8b). At least in theory, Louisiana may be reciprocally dependent upon Texas for offshore spawning by brown shrimp to replenish postlarvae in its estuaries each year.

Temporal effect. Under most circumstances, hypoxia is not a year-long phenomena [Rabalais et al., 1991]. Although the occurrence arrives and disappears, its size, timing and duration may change the consequences for shrimp. Early spring hypoxia could negatively impact recruitment of brown shrimp postlarvae into nurseries. Large-scale, nearshore hypoxia during the spring could impinge on white shrimp spawning areas. Large-scale summer hypoxia can impede brown shrimp juveniles from moving offshore. Extension of summer hypoxia shoreward may adversely crowd shrimp and intensify fishery trawling effort in localized areas.

Influence of Spawning and Feeding Habitat

Shrimp spawning grounds in Louisiana are likely impacted by hypoxia. The spawning area for white shrimp can be reduced during the spring and summer when hypoxia extends close to shore and the timing and location of both events coincide. Spawning grounds of brown shrimp may be eliminated entirely in offshore Louisiana during the months in which hypoxia occurs. The re-routing of juveniles into Texas waters during summer months may also lead to lower numbers of adult brown shrimp offshore of Louisiana after hypoxia disappears. Fall and winter months are the peak spawning period for brown shrimp.

Summer hypoxia in a band along the coast blocks access of juvenile shrimp migrating to offshore feeding grounds. In areas where severe hypoxia has killed infaunal annelid worms [Harper and Rabalais, 1997] which are important prey for brown shrimp [McTigue and Zimmerman, 1998] the forage value of habitat may be diminished (see Rabalais et al. [this volume]). Losses in production due to lost feeding and impairment of growth are difficult if not impossible to determine, but theoretically they may be significant and especially so for brown shrimp. Such losses in productivity only exacerbate when the hypoxic zone expands in space and time.

References

Baxter, K. N. and W. C. Renfro, Seasonal occurrence and size distribution of postlarval brown and white shrimp near Galveston, Texas with notes on species identification, *U.S. Fish Wildl. Serv., Fish. Bull., 66*, 149-158, 1967.

Bryan, C. E. and T. J. Cody, A study of commercial shrimp, rock shrimp and potentially commercial finfish 1973-1975, in *Part I. White Shrimp, Penaeus setiferus (Linn.), Spawning in the Gulf of Mexico off Texas Coast*, Fish. Branch, Texas Parks and Wildl. Dept., P.L. 88-309 Proj. 2-202-R:1-29, 1975.

Christmas, J. Y. and D. J. Etzold, The shrimp fishery of the Gulf of Mexico United States: a regional management plan. *Tech. Rep. No. 2*, Gulf Coast Research Laboratory, Ocean Springs, Mississippi, 1977.

Condrey, R. E. and D. Fuller, The U.S. Gulf shrimp fishery, in *Climate Variability, Climate Change, and Fisheries*, edited by M. H. Glantz, pp. 89-119, Cambridge University Press, New York, 1992.

Cook, H. L. and M. J. Lindner, Synopsis of biological data on the brown shrimp *Penaeus aztecus* Ives, 1891, *FAO Fish. Rep. (57) 4*, 1471-1497, 1970.

Downing, J. A., J. L. Baker, R. J. Diaz, T. Prato, N. N. Rabalais, and R. J. Zimmerman, Gulf of Mexico Hypoxia: Land and Sea Interactions, *Council for Agricultural Science and Technology, Task Force Report No. 134*, 44 pp., 1999.

Gazey, W. J., B. J. Galloway. R. C. Fechhelm, L. R. Martin, and L. A. Reitsema, Shrimp mark and release and port interview sampling survey of shrimp catch and effort with recovery of captured tagged shrimp, in *Shrimp Population Studies: West Hackberry and Big Hill Brine Disposal Sites Off Southwest Louisiana and Upper Texas Coasts, 1980-1982*, Vol. III, edited by W. B. Jackson, 306 pp., Department of Commerce NOAA/NMFS Final Report to U. S. Department of Energy, 1982.

Harper, Jr., D. E. and N. N. Rabalais, Responses of benthonic and nektonic organisms, and communities, to severe hypoxia on the inner continental shelf of Louisiana and Texas, in Proc., First Gulf of Mexico Hypoxia Management Conference, December 1995, New Orleans, Louisiana, pp. 41-65, Publ. No. EPA-55-R-97-001, Gulf of Mexico Program Office, Stennis Space Center, Mississippi, 1997.

Holiday, M. C. and B. K. O'Bannon, *Fisheries of the United States, 1998*, Current Fisheries Statistics No. 9800, National Oceanic and Atmospheric Administration/National Marine Fisheries Service, Washington, D.C., 1999.

Klima, E. F., K. N. Baxter, and F. J. Patella, A review of the offshore shrimp fishery and the 1981 Texas closure, *Mar. Fish. Rev., 44*, 16-30, 1982.

Leming, T. D. and W. E. Stuntz, Zones of coastal hypoxia revealed by satellite scanning have implications for strategic fishing, *Nature, 310*, 136-138, 1984.

Lindner, M. J. and W.W. Anderson, Growth, migrations, spawning and size distribution of shrimp, *Penaeus setiferus, U.S. Fish Wildl. Serv., Fish Bull., 106*, 554-645, 1956.

Lindner, M. J. and H. L. Cook, Synopsis of biological data on the white shrimp *Penaeus setiferus* (Linn.), 1767, *FAO Fish. Rep., 57*, 1439-1469, 1970.

Loesch, H., Sporadic mass shoreward migrations of demersal fish and crustaceans in Mobile Bay, Alabama, *Ecology, 41*, 292-298, 1960.

Louisiana Department of Wildlife and Fisheries, A Fisheries Management Plan for Louisiana's Penaeid Shrimp Fishery, 231 pp., 1992.

Lyon, J. M., and C. J. Boudreaux, Movement of tagged white shrimp, Penaeus setiferus, in the northwestern Gulf of Mexico, *Louisiana Dept. Wildl. Fish. Tech. Bull., 39,* 1-32, 1983.

McTigue, T. A. and R. J. Zimmerman, The use of infauna by juvenile *Penaeus aztecus* Ives and *Penaeus setiferus* (Linnaeus), *Estuaries, 21,* 160-175, 1998.

Moffett, A. W., The shrimp fishery in Texas, *Texas Parks and Wildl. Dept. Bull. 50,* 36 pp., 1967.

Nance, J. M., Stock assessment for brown, white and pink shrimp in the U. S. Gulf of Mexico, 1960-1987, *NOAA Tech. Memo., NMFS-SEFSC-221,* 65 pp., 1989.

Nance, J. M., Estimation of Effort for the Gulf of Mexico Shrimp Fishery, *NOAA Tech. Memo., NMFS-SEFSC-300,* 12 pp., 1992.

Nance, J. M., Effort Trends for the Gulf of Mexico Shrimp Fishery, *NOAA Tech. Memo., NMFS-SEFSC-337,* 37 pp., 1993.

Nance, J. M., and D. Harper, Southeast and Caribbean invertebrate fisheries, in *Our Living Oceans, Report on the status of U.S.Lliving Marine Resources, 1999,* U.S. Dept. Commerce, *NOAA Tech. Memo. NMFS-F/SPO-41,* 143-147, 1999.

Nance, J. M., E. X. Martinez, and E. F. Klima, Feasibility of improving the economic return from the Gulf of Mexico brown shrimp fishery, *N. Amer. J. Fish. Mgt., 14,* 522-536, 1994.

Perez-Farfante, I. and B. F. Kensley, Penaeoid and sergestoid shrimps and prawns of the world, keys and diagnoses for families and genera, *Mem. Mus. natn. Hist. nat., 175,* 1-233, 1997.

Rabalais, N. N., R. E. Turner, W. J. Wiseman, Jr., and D. F. Boesch, A brief summary of hypoxia on the northern Gulf of Mexico continental shelf: 1985-1988, in *Modern and Ancient Continental Shelf Anoxia,* edited by R. V. Tyson and T. H. Pearson, pp. 35-47, *Geological Society Special Publ., 58,* 1991.

Rabalais, N. N., R. E. Turner, and W. J. Wiseman, Jr., Distribution and characteristics of hypoxia on the Louisiana shelf in 1990 and 1991, in Nutrient Enhanced Coastal Ocean Productivity Workshop Proceedings, pp. 15-20, Publ. No. TAMU-SG-92-109, Texas A&M University Sea Grant College Program, College Station, Texas, 1992.

Rabalais, N. N., R. E. Turner, W. J. Wiseman, Jr. and Q. Dortch, Consequences of the 1993 Mississippi River Flood in the Gulf of Mexico, *Regulated Rivers: Research & Management, 14,* 161-177, 1998.

Rabalais, N. N., R. E. Turner, D. Justic', Q. Dortch, and W. J. Wiseman, Jr., Characterization of hypoxia: Topic 1 Report for the Integrated Assessment of Hypoxia in the Gulf of Mexico. NOAA Coastal Ocean Program Decision Analysis Series No. 16, NOAA Coastal Ocean Program, Silver Springs, Maryland, 167 pp., 1999.

Renaud, M. L., Hypoxia in Louisiana coastal waters during 1983: implications for fisheries, *U.S. Fish Wildl. Serv., Fish Bull., 84,* 19-26, 1986a.

Renaud, M. L., Detecting and avoiding oxygen deficient sea water by brown shrimp, *Penaeus aztecus* (Ives), and white shrimp *Penaeus setiferus* (Linnaeus), *J. Exp. Mar. Biol. Ecol., 98,* 283-292, 1986b.

Sheridan, P. F., R. G. Castro M., F. J. Patella, Jr., and G. Zamora, Jr., Factors influencing recapture patterns of tagged penaeid shrimp in the western Gulf of Mexico, *U.S. Fish Wildl. Serv., Fish Bull., 87,* 295-311, 1989.

Springer, S., The *Oregon*'s fishery explorations in the Gulf of Mexico, 1950, *Com. Fish. Rev., 13,* 1-8, 1951.

Zimmerman, R., J. Nance, and J. Williams, Trends in shrimp catch in the hypoxic area of the northern Gulf of Mexico, in Proc., First Gulf of Mexico Hypoxia Management Conference, December 1995, New Orleans, Louisiana, pp. 64-74, Publ. No. EPA-55-R-97-001, Gulf of Mexico Program Office, Stennis Space Center, Mississippi, 1997.